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A Simple EHF Hemispheric Coverage Antenna

J.C. Lee

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Lincoln Laboratory

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LEXINGTON, MASSACHUSETTS

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Gary Tutungian

Gary Tutungian
Administrative Contracting Officer
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Group 63

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ABSTRACT

A circularly polarized, axially symmetric, wide-beam radiator is required in many applications, including TT&C for UAVs and satellites. This report discusses some existing wide-beam antenna designs including divergent lenses and reflectors and introduces a new antenna design. Using a simple dielectric ring in conjuction with a dielectric loaded circular waveguide opening, a near ideal, axially symmetric, hemispheric coverage antenna with circular polarization of good axial ratio and wide-band impedance match is realized. Mechanically, the antenna is small, lightweight, and low cost. The dielectric used is the common Rexolite. Since no lossy materials or resonant scatterers are used, the antenna performance is inherently broadband and low loss. A K_a-band prototype as well as compact designs for both Q- and K-bands are described.

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1. INTRODUCTION

A circularly polarized, axially symmetric, wide-beam radiator is required for many applications in the microwave and millimeter-wave (MM) frequency range. Some examples are telemetry, tracking, and command (TT&C) antennas on unmanned aerial vehicles (UAVs) and spacecraft, airborne microwave landing system antennas, antennas for paging, beacon, homing, and wireless communication systems, and global positioning system (GPS) receive antennas.

An isotropic or omni coverage antenna may be ideal for many of these applications, but nature will not permit a true omni antenna [1]. However, wide-beam antennas with hemispheric coverage are theoretically possible. Two such antennas, whether back-to-back switched or connected to different receivers and transmitters, can be used to fulfill a required omni coverage mission.

Lincoln Laboratory initiated an antenna development program on a low-priority basis in late 1990, aimed at the development of a small, lightweight, hemispheric coverage antenna operating in the EHF satellite communication band. This report discusses some existing wide-beam antenna designs and introduces a new antenna design [2] that is simple, small, and lightweight, and achieves near ideal hemispheric coverage. Specific design features of this antenna and some of its measured performance results are described.

2. BACKGROUND

Wide-beam radiator technology can be divided into three categories: TEM-dipole, geometric-optic, and waveguide-horn. The TEM-dipole approach is generally applicable to the low RF frequencies and uses microstrip patch antennas [3,4], short helices [5], cross-dipoles [6], or cross-slots [7]. The TEM-dipole is not practical for microwave and MM-wave frequencies because of the antenna complexity, tight fabrication tolerances, and high losses. The geometric-optic category applies to the very high RF frequencies and uses divergent lenses and reflectors [8,9]. Although hemispherical coverage can be obtained at the MM-wave frequencies using this technique, the resulting antennas are, in general, too large and heavy for many applications. The waveguide-horn approach uses the size of the horn aperture to control the antenna beamwidth. Unfortunately the 3-dB beamwidth cannot be increased much beyond 60 degrees without appreciable pattern deterioration.

Examples of EHF broad-beam antenna designs using the geometric-optic approach are described in Reference 9. Lee and Hwang describe two antenna designs intended for the EHF TT&C satellite application: one using a divergent lens; the other using a divergent reflector.

For operation at 44 GHz the required lens diameter is 16 inches. (See Figure 1.) Figure 2 shows the calculated pattern. A 4-dB beamwidth of about 180 degrees can be achieved. Although this antenna can provide a good broad pattern, because of its bulky form and heavy weight, it is not the best candidate for many applications.

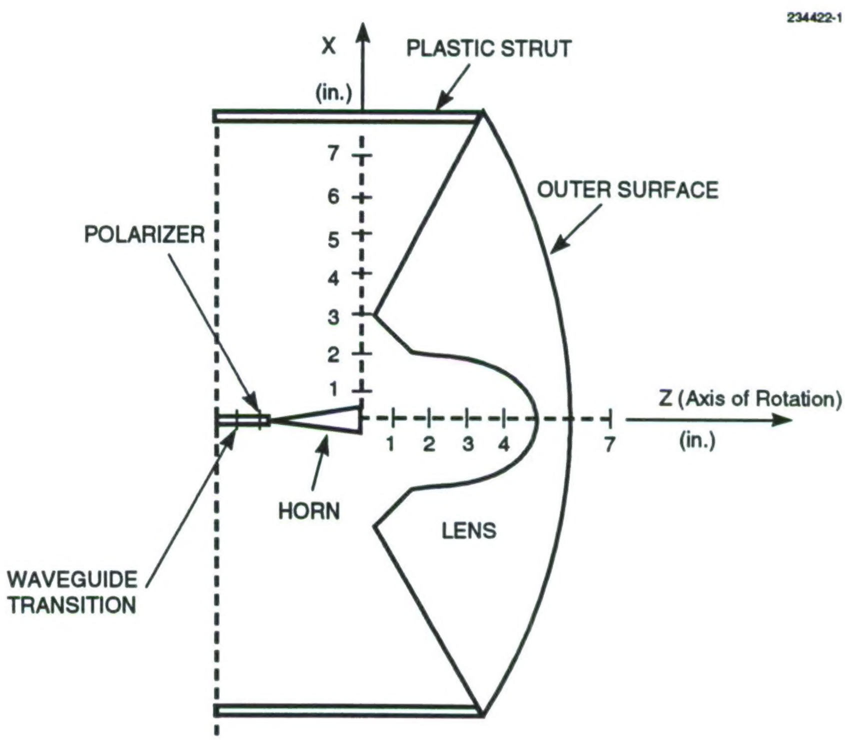

Figure 1. Wide-beam lens antenna.

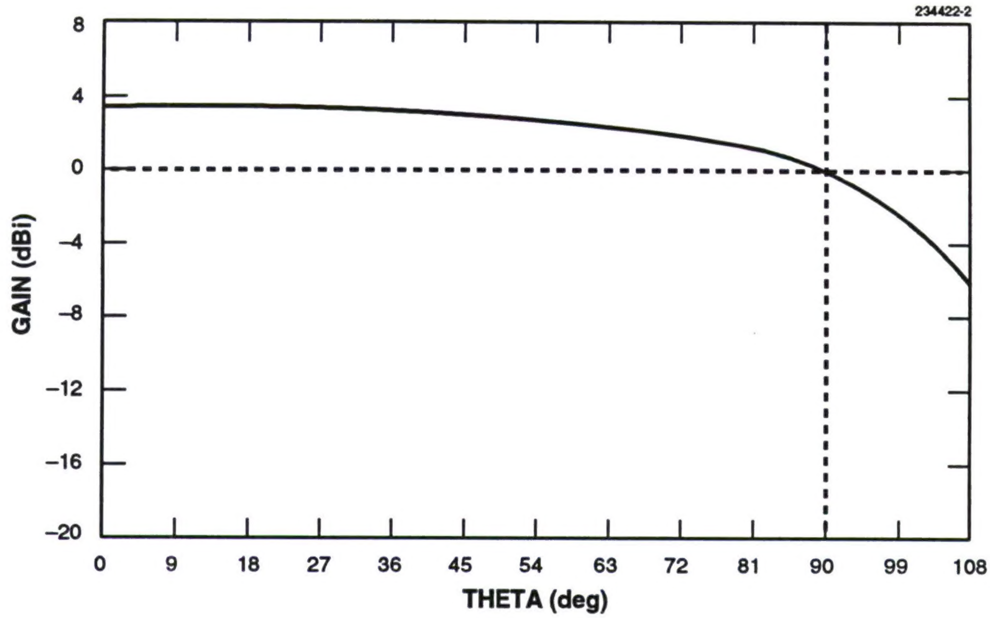

Figure 2. Calculated ideal wide-beam patterns.

The reflector antenna shown in Figure 3 uses a reflector with a diameter of about 6 inches. The axial length is about 10 inches. The (perhaps optimistic) estimated weight is about 1 pound. Figure 4 shows the measured reflector antenna pattern. A small lens could be used to smooth, to some extent, the strong interference ripples occurring within about 30 degrees of the axial direction that are caused by the feed horn and strut blockage. Such a lens may limit the peak-to-peak pattern variations to about 5 dB close to the axial direction.

Another design approach uses a cross-shaped parasitic radiator in front of an open waveguide to direct radiation toward a recessed conical reflector [10]. Figure 5 shows the antenna construction for a K_u-band design (15.9 to 18.0 GHz). The length of this antenna could be reduced to about 6 inches by integrating the polarizer into the dielectric rod and simplifying the orthomode transducer (OMT) design. Figure 6 shows measured patterns taken with a spinning linear source. Note that there is no measurable interference pattern due to feed blockage. The oscillation on the patterns shows the axial ratio. The polarizer seems to work best at 18 GHz. The 3-dB beamwidths (about 160 degrees) are a bit narrow for ideal hemispheric coverage.

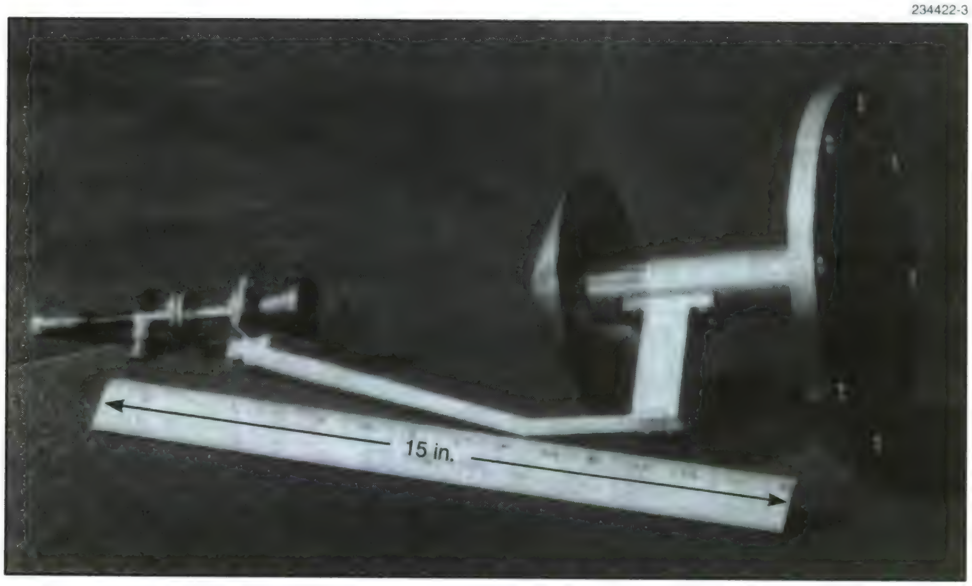

Figure 3. Wide-beam reflector antenna.

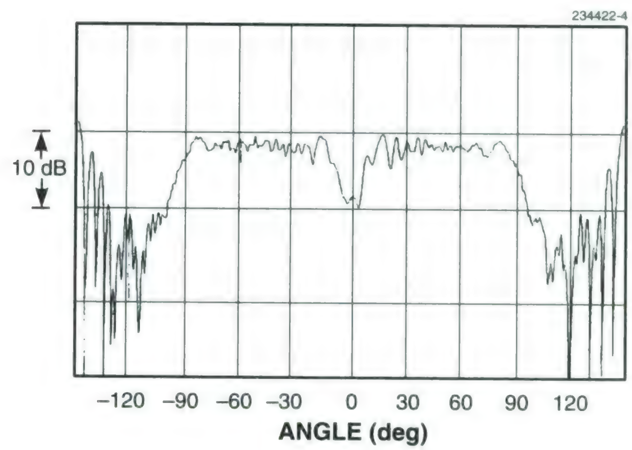

Figure 4. Measured reflector antenna pattern.

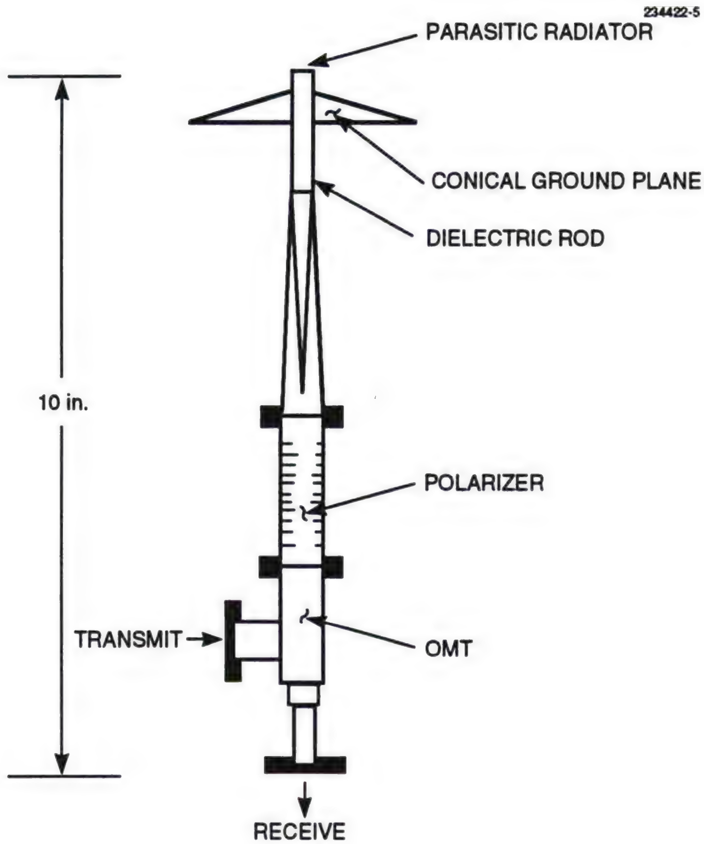

Figure 5. A K_u-band wide-beam antenna design.

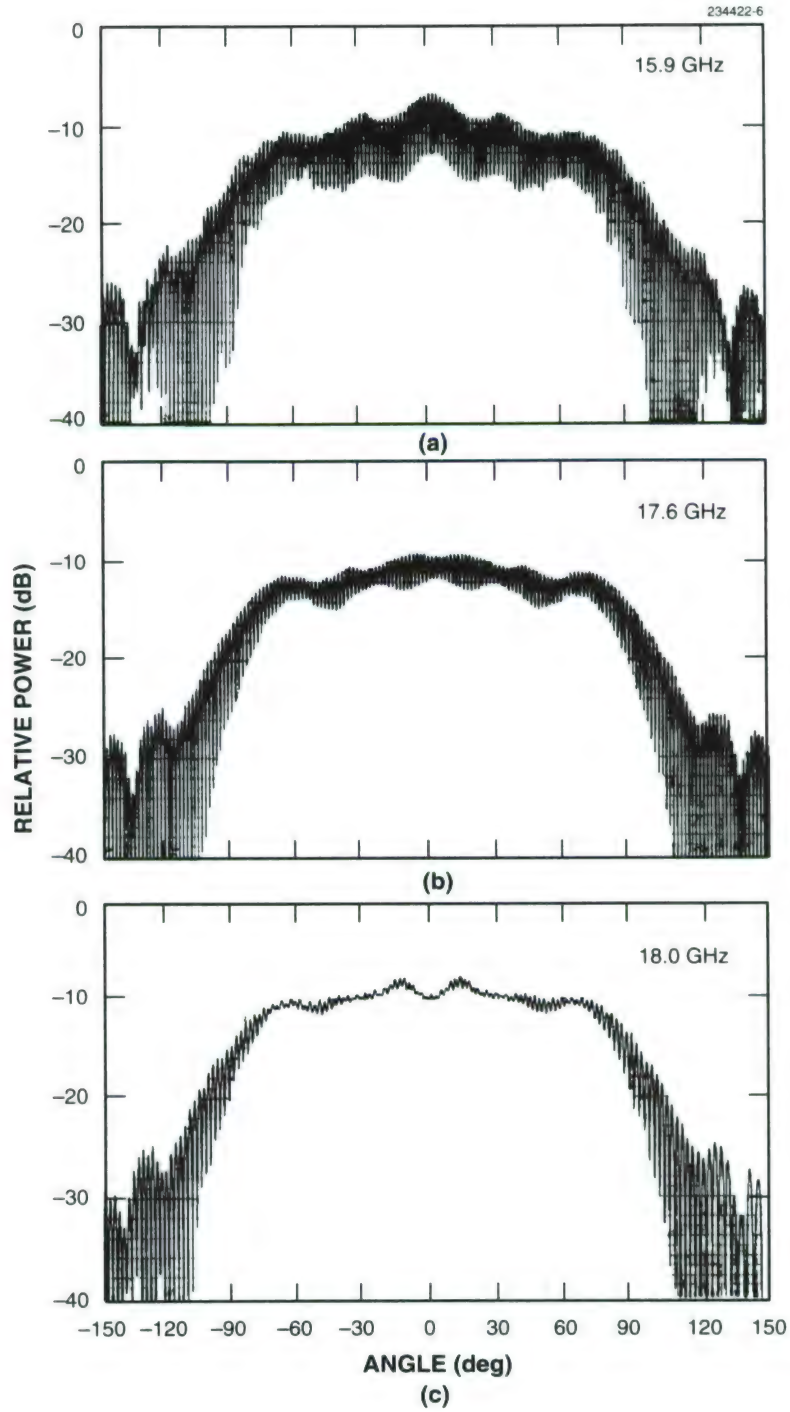

Figure 6. A K_u-band antenna pattern.

3. DESIGN APPROACH

As mentioned earlier, the estimated weight for the divergent reflector antenna is about 1 pound for the 44-GHz design. The weight will be significantly more for a 20-GHz antenna. If a wide-beam antenna using the open waveguide approach can be realized, a weight reduction by at least an order of magnitude may be achievable.

In view of the obvious disadvantages (size and weight) of the geometric-optic approach and the inherent high loss and narrow bandwidth of the TEM-dipole approach, Lincoln Laboratory chose to investigate the waveguide-horn approach. In particular, the investigation concentrated on devising schemes to improve the relatively poor antenna performance inherent in this approach.

In the horn antenna design, it is well known that, within certain limitations, the smaller the aperture, the broader the beam. Taking this approach to its limit, the "horn opening" becomes an open-ended waveguide. Further reduction of the aperture size requires the introduction of waveguide ridges or dielectric loading in order to maintain the appropriate cutoff frequency. Generally, this results in narrow bandwidth and disparity in the E- and H-plane radiation patterns.

Other techniques used to broaden the beam include the use of parasitic probes and slots [11,12], multiple cross-dipoles (Figure 7), or specially shaped parasitic radiators around or in front of the waveguide opening in conjunction with a conical ground plane (a form of a divergent reflector) [10,13,14]. These are usually complicated and quite sensitive to dimensional tolerances, particularly at EHF.

Another technique to beam broadening uses a specially shaped dielectric plug [15,16]. Figure 8 depicts a plug design. However, measured pattern results show beam disparity and frequency sensitivity problems, as shown in Figure 9.

In this investigation, various schemes to achieve beam broadening were tried, including the use of slots in the waveguide opening rim and dielectric rods and plugs with simple shapes. The scheme finally chosen uses a simple dielectric ring. Dielectric rings have been used to narrow the antenna beam [17], but it was found that with the appropriate design they could also be used to broaden it.

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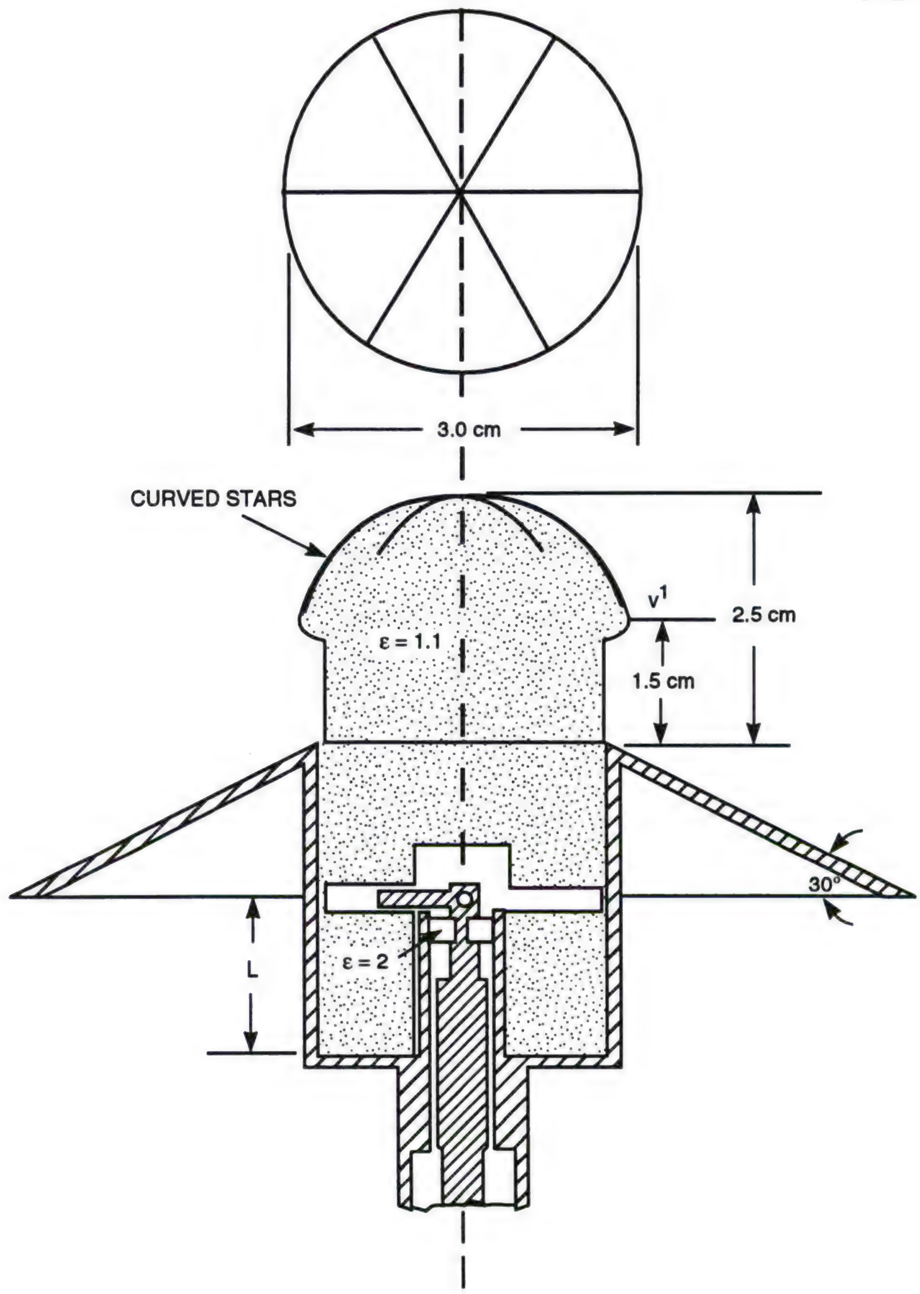

Figure 7. Cross-dipole beam broadening design.

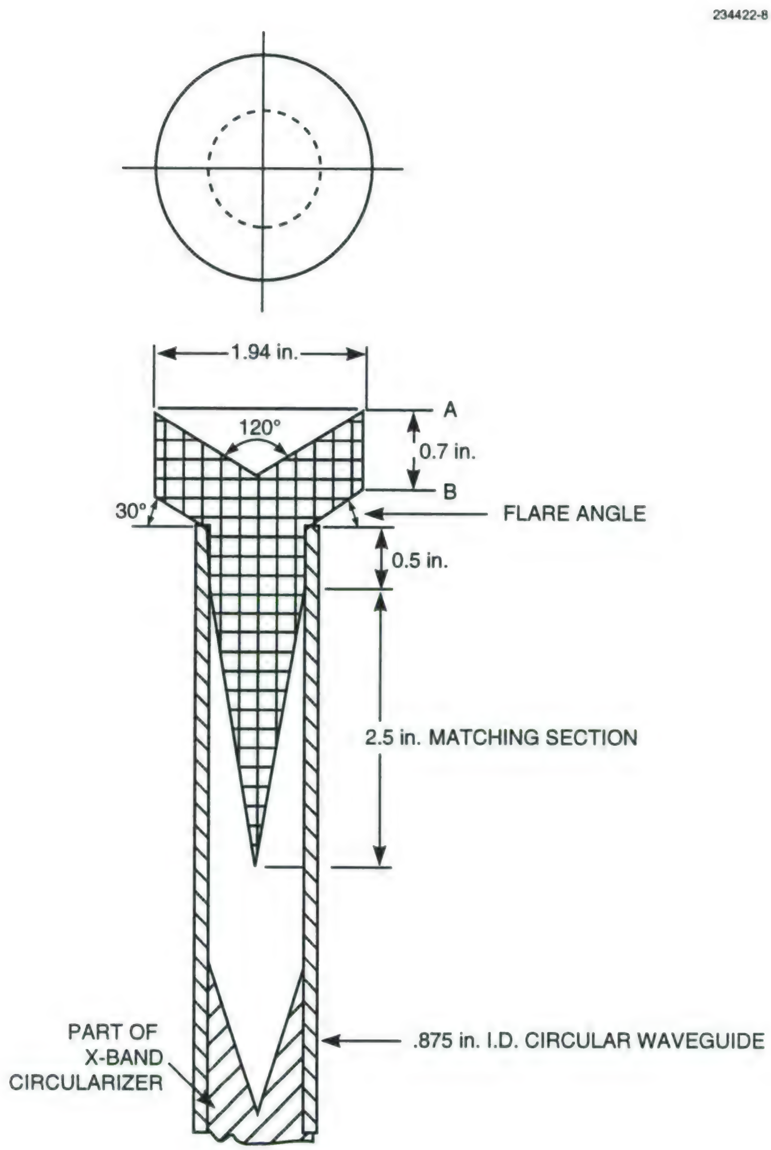

Figure 8. Shaped dielectric plug design.

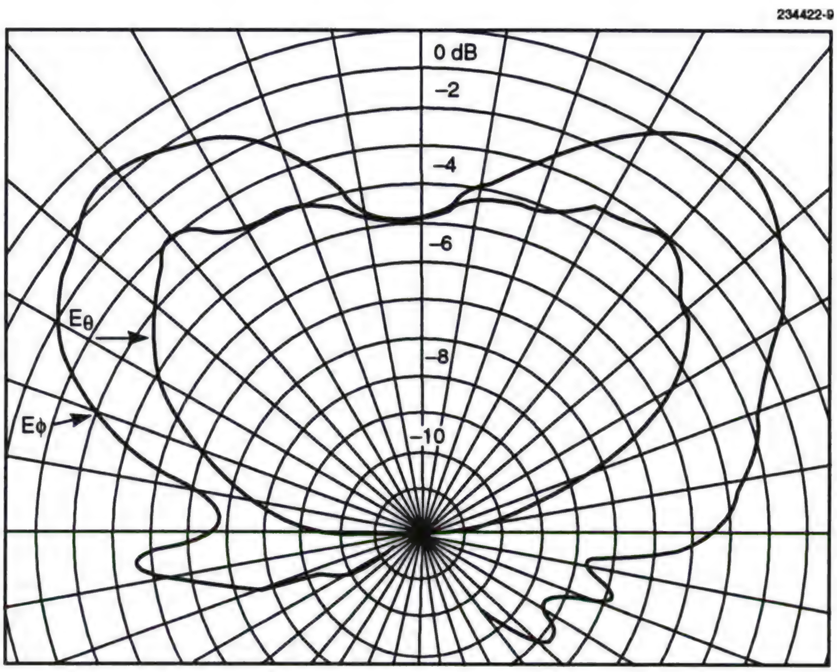

Figure 9. Shaped dielectric plug performance.

4. ANTENNA DESIGN AND PERFORMANCE

Currently, accurate predictions of the performance of dielectric resonators can only be calculated for high dielectric constant materials (e.g., $K \geq 9$) with simple geometries such as cylinders [18]. Since this approach uses a ring geometry with relatively low dielectric constant, the development of the design was largely empirical.

The design uses a dielectric ring around the waveguide opening rim to shape the antenna patterns. A small corrugated flange has also been added to reduce back radiation. Figure 10 shows a K_a-band breadboard model of the antenna. Preliminary measured patterns without a circular polarizer are shown in Figures 11–14. Note the extremely broad and axially symmetric beam patterns. The measured E- and H-plane patterns shown were taken over the band, 31.5 to 33 GHz. Without a polarizer, the antenna is linearly polarized, but the close match of the E- and H-plane patterns indicates that, with the addition of a polarizer, a very low axial ratio is achievable.

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Figure 10. K_a-band dielectric ring antenna design.

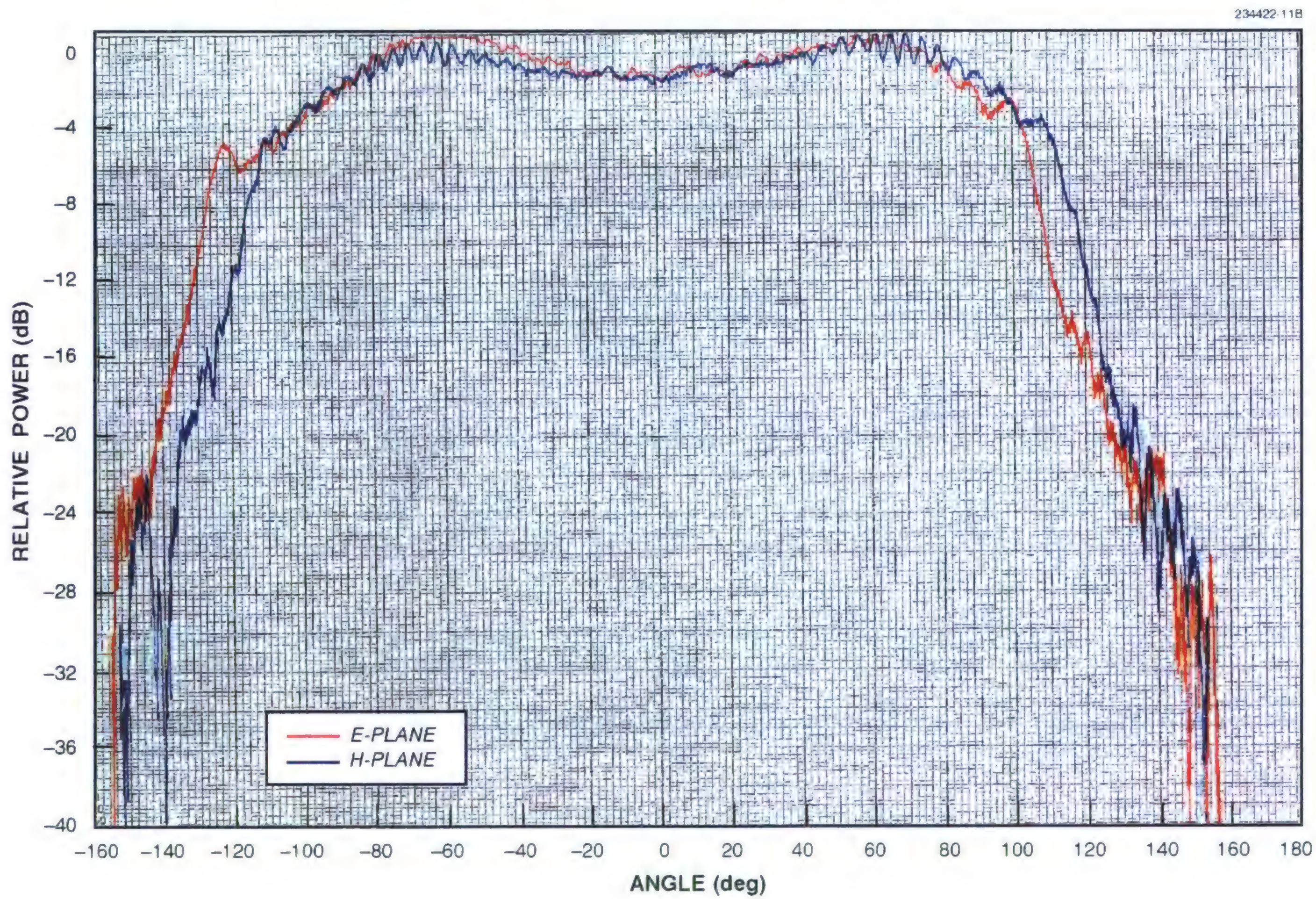

Figure 11. *K_a-band antenna performance, 31.5 GHz.*

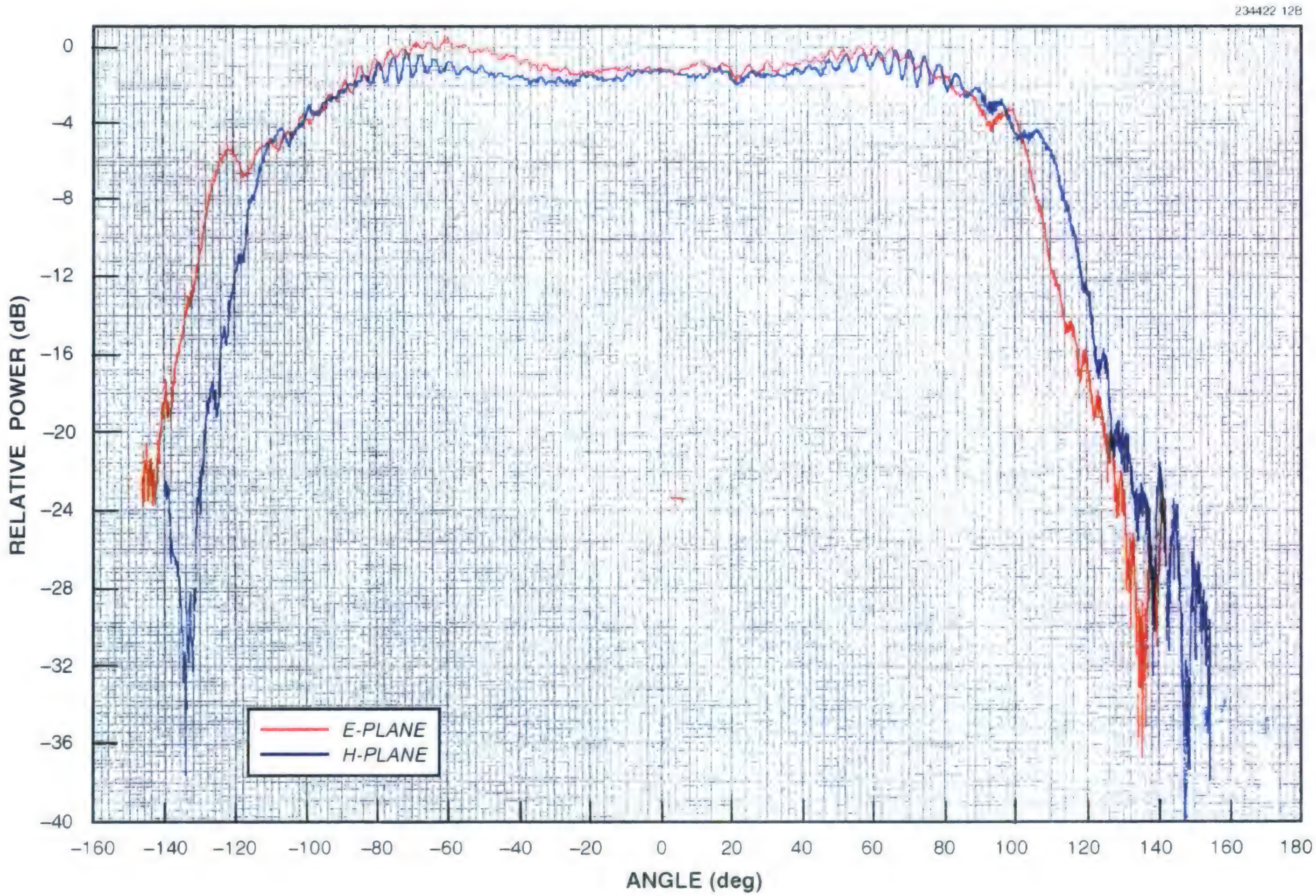

Figure 12. K_a*-band antenna performance, 32.0 GHz.*

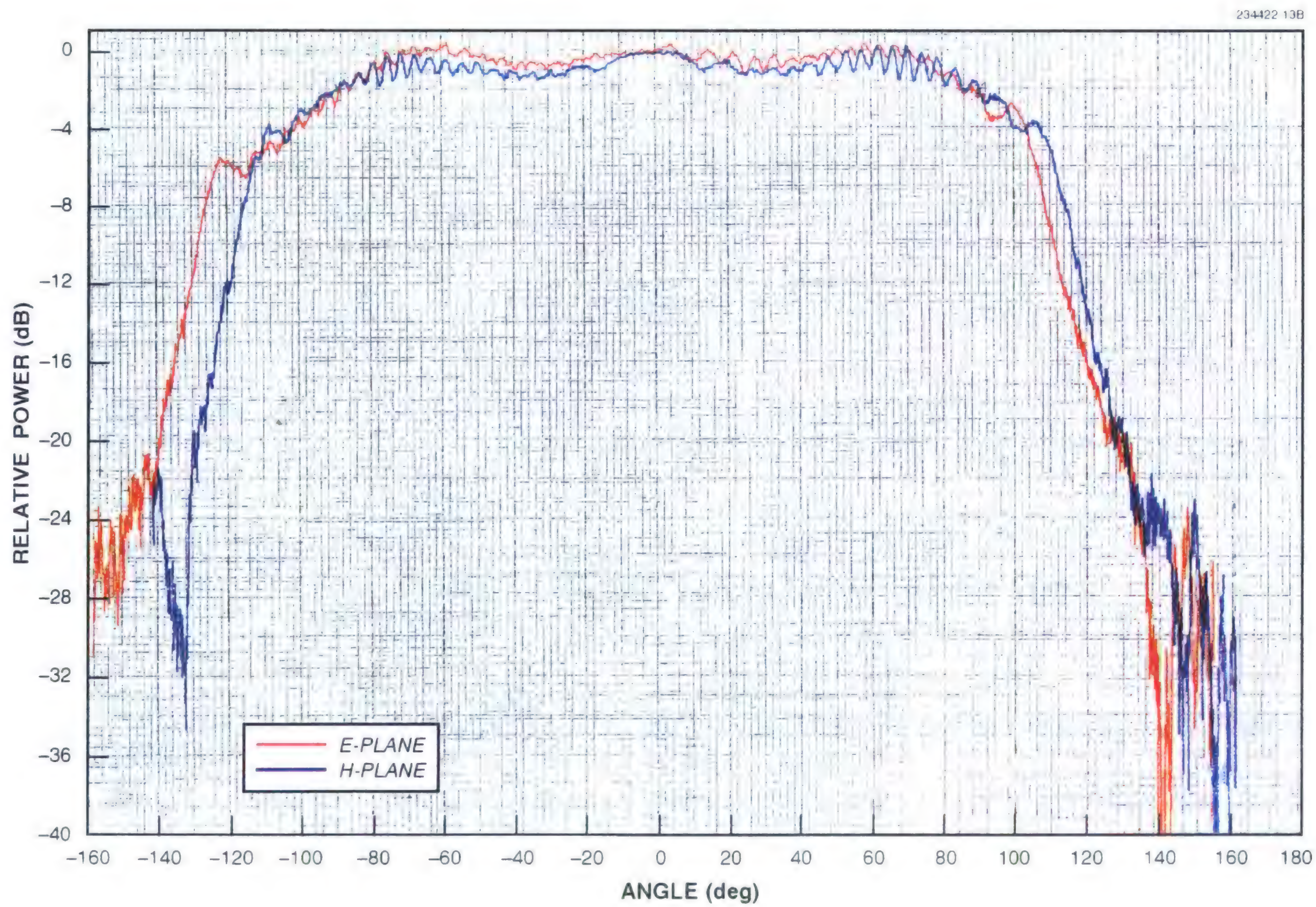

Figure 13. K_a-band antenna performance, 32.5 GHz.

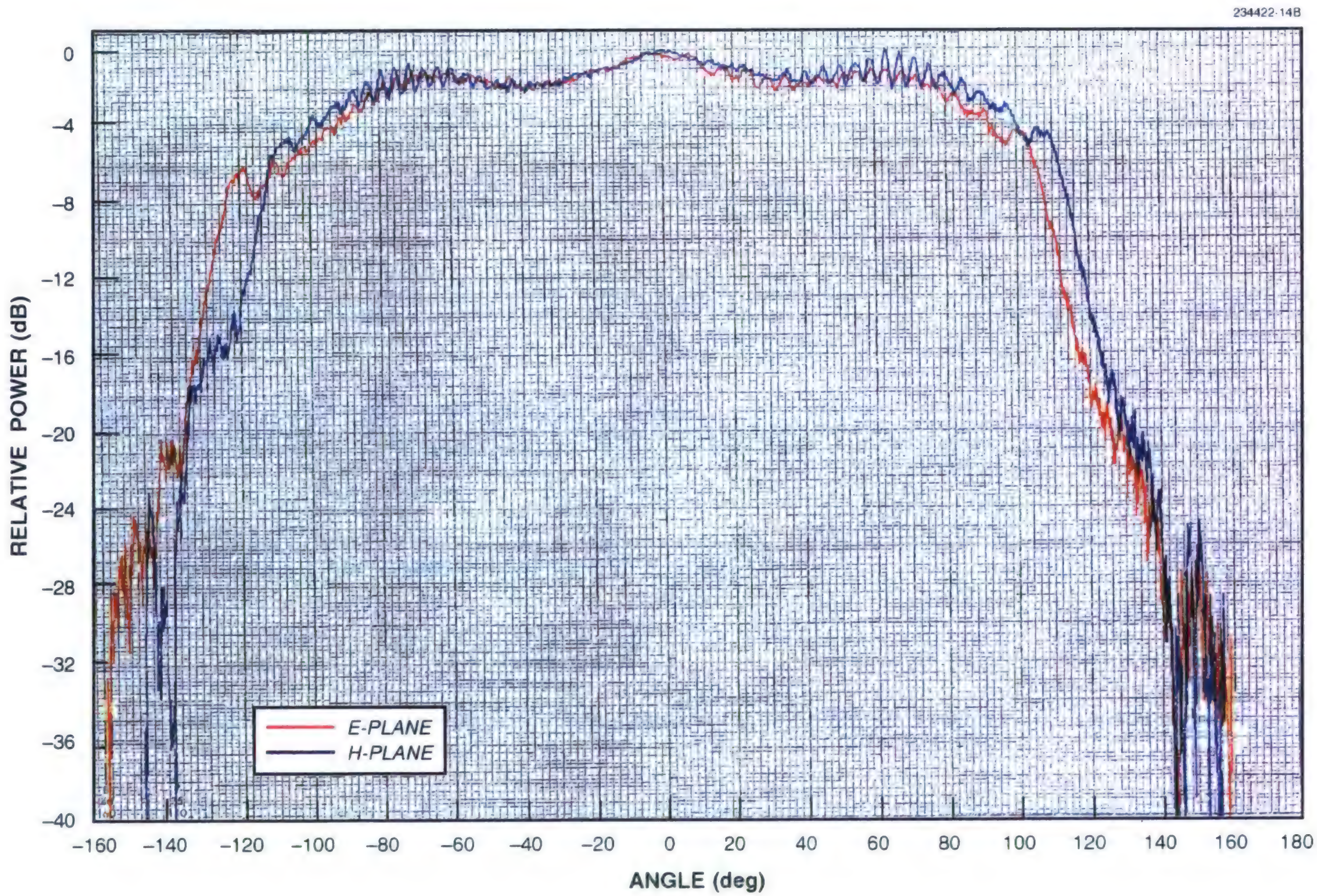

Figure 14. K_a-band antenna performance, 33.0 GHz.

This test model, including the rectangular-to-circular waveguide transition, was designed with a total length of about 5 inches so that possible modifications and adjustments could be easily made. A final model could be much shorter. Figures 15 and 16 show K-band (20 GHz) and Q-band (44 GHz) models. Again, the threads at the metal tube ends and in the dielectric rings are retained for easy adjustment. In a final design such threads would be omitted. Figure 17 gives dimensions for the Q-band antenna.

A Q-band model measures about 2 inches in length and weighs 2.5 ounces. The length of the antenna is primarily determined by the tapered rectangular-to-circular waveguide transition. This transition can be simplified by a single quarter-wave transformer of about 0.1 inch length, which can be built inside the flange. Without the tapered transition, the length is less than 1 inch and about 0.9 ounce in weight. The use of aluminum rather than copper and brass and a smaller waveguide flange would result in a weight of about 0.25 ounce. Compared with the estimated 1-pound weight for the divergent reflector approach, the present design promises to be almost 50 times lighter. For the K-band antenna, the estimated length is 1 inch and the weight is about 0.5 ounce.

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Figure 15. K-band antenna picture.

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Figure 16. Q-Band antenna picture.

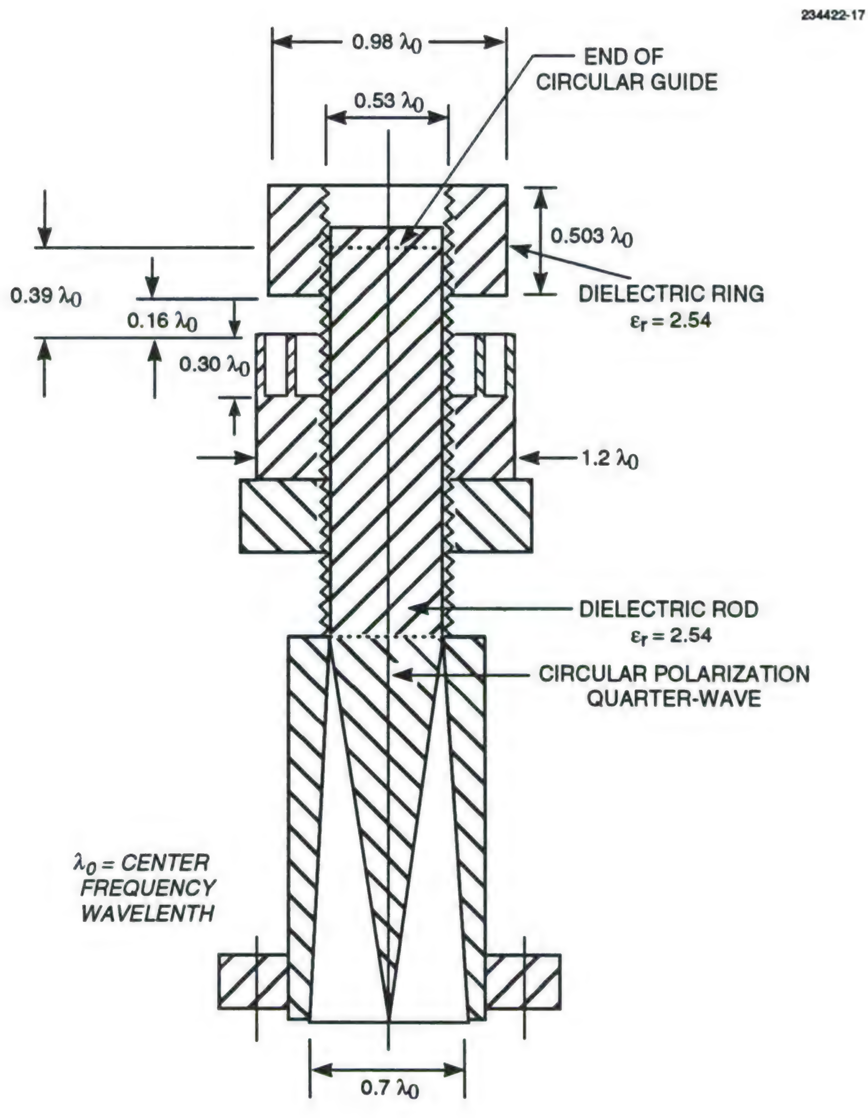

Figure 17. Q-band antenna dimensions.

Measurements have shown that the antenna pattern is mainly determined by the dielectric ring size and location. The antenna pattern is rather insensitive to the dielectric rod protrusion. Measured antenna patterns with the rod flush with the metal tube opening and with a built-in quarter wave plate to replace the tapering end of the dielectric rod inside the metal tube are shown in Figures 18–24. The patterns were measured with a rotating linearly polarized antenna. Note that good antenna patterns with low axial ratio were achieved over a very broad frequency range (41 to 47 GHz).

Tests have shown that impedance match is sensitive to the dielectric rod protrusion. With the dielectric rod flush to the metal tube opening, the return losses were about 9 dB. When the dielectric rod protrudes out of the metal tube, flush with the dielectric ring, a better impedance match is achieved (return loss more than 15 dB) over a very broad frequency range. This is shown in Figure 25. A Smith chart plot shows that the impedance locus is bunched together; this implies that the match can be further improved by adding a single appropriate matching element.

The dielectric material used is Rexolite. Tests, however, show that low-loss materials with dielectric constants in the range of 2.1 to 4.0 will work well with some adjustment of ring dimensions. This range of dielectric constant spans the best-behaving dielectrics (low loss, wide frequency band, high temperature, high thermal conductivity, etc.) including Teflon, Rexolite, fused quartz, and boron nitride.

Some preliminary antenna gains were measured over a limited (41 to 43 GHz) band. Gain data in the axial direction varies between 4 and 2 dBi. These rather low gains are fundamentally due to the antenna's broad beam. Judging from the good impedance match and that no lossy material is used, these antenna gains may represent the best achievable.

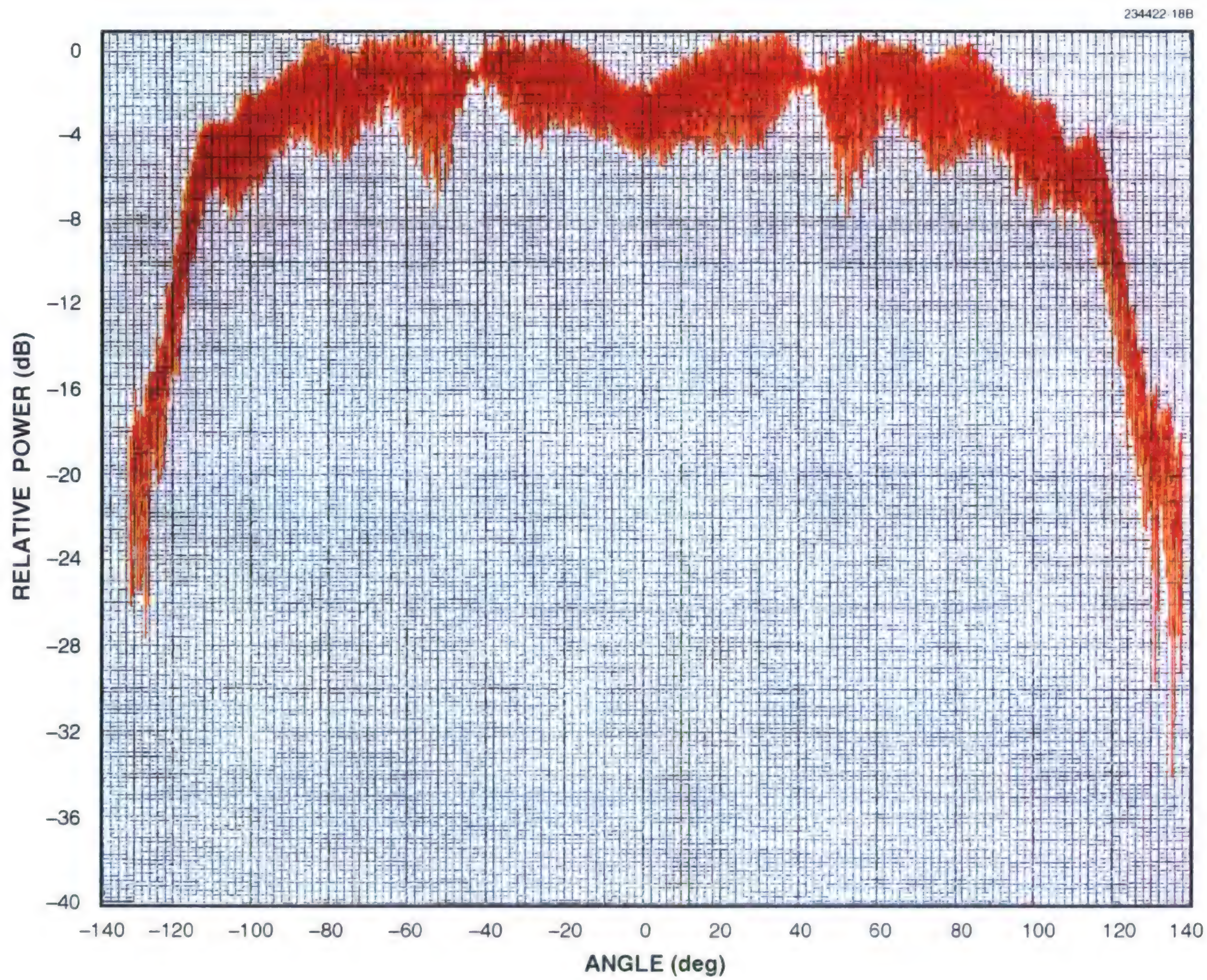

Figure 18. Q-band antenna performance, 41 GHz.

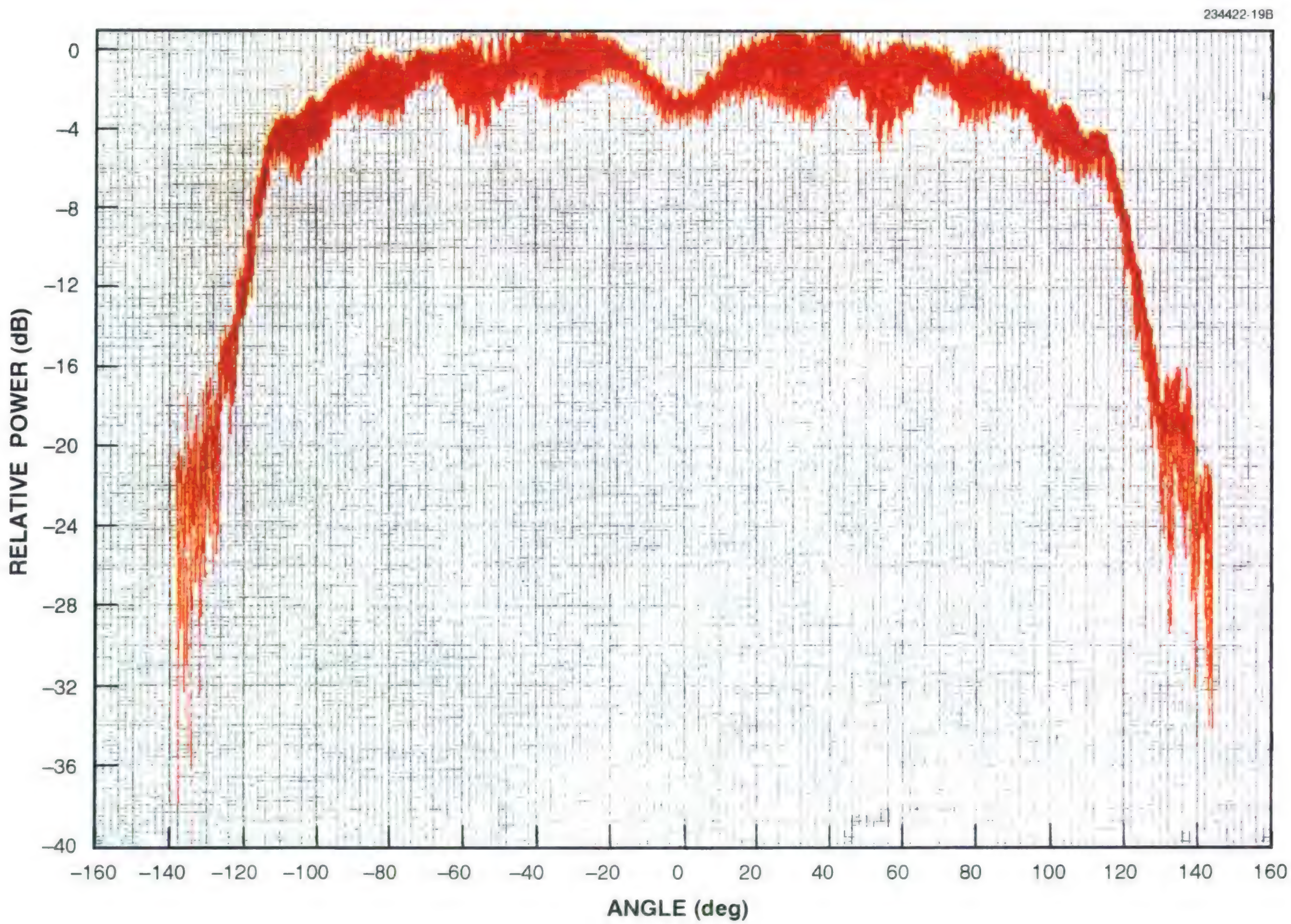

Figure 19. Q-band antenna performance, 42 GHz.

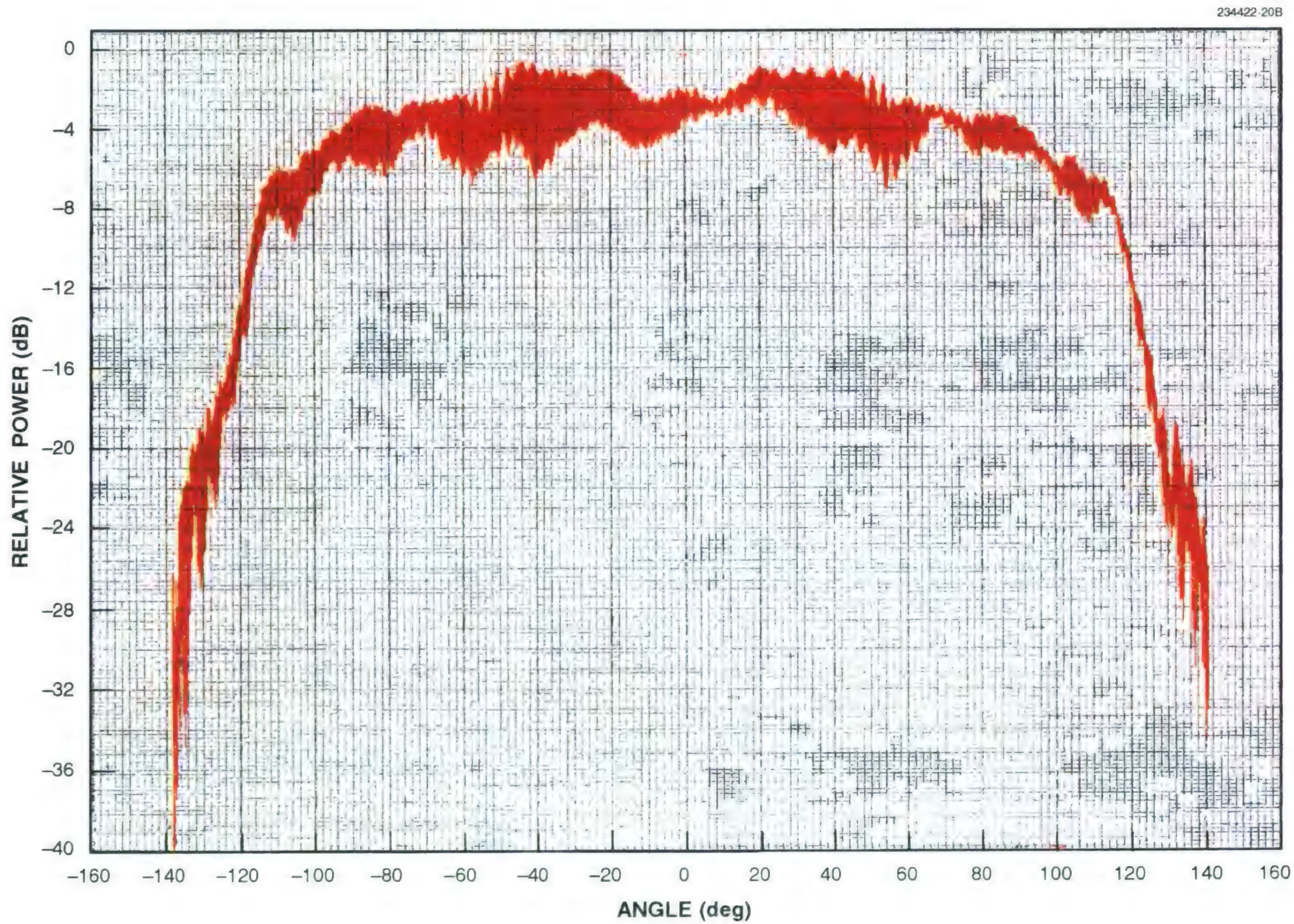

Figure 20. Q-band antenna performance, 43 GHz.

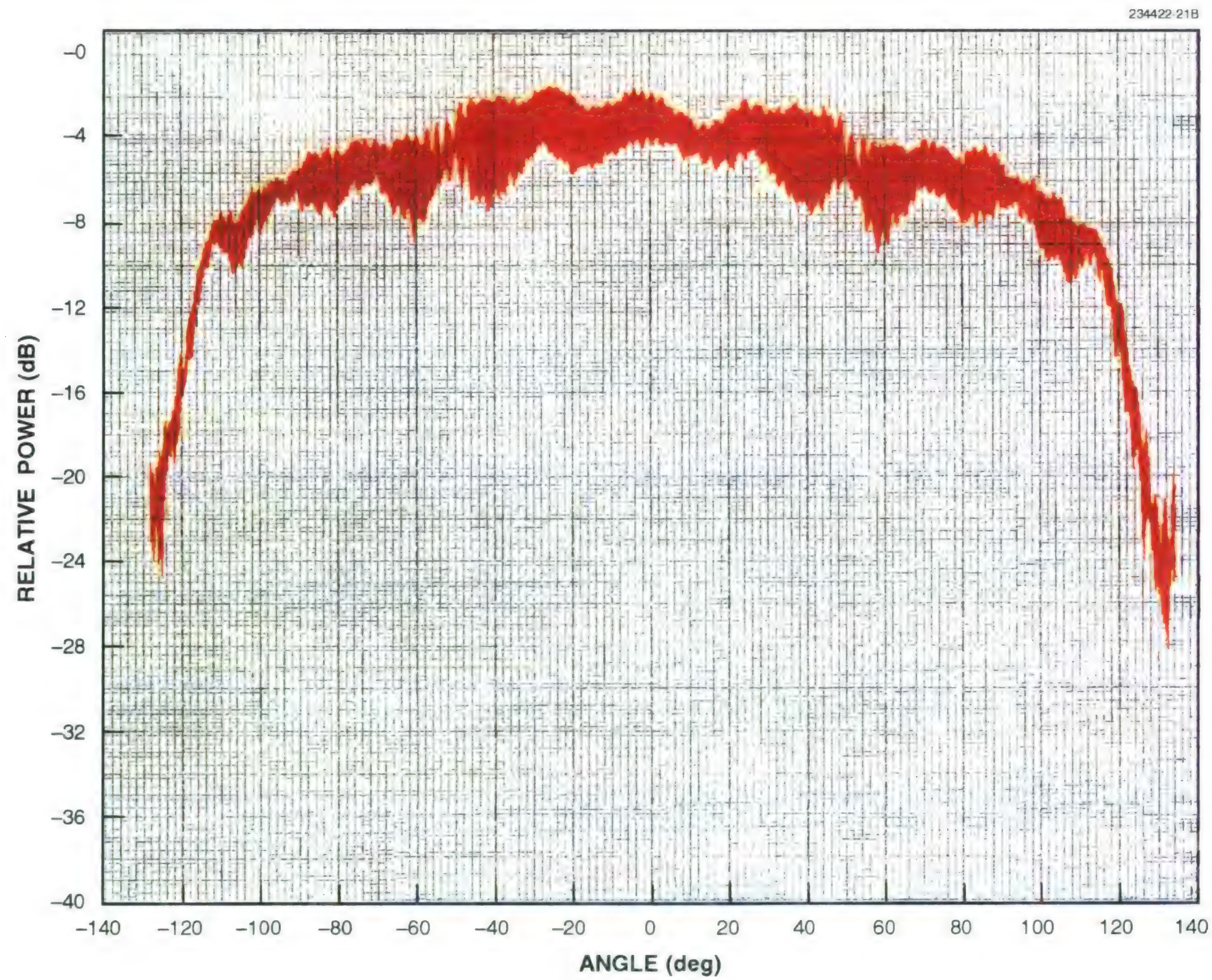

Figure 21. Q-band antenna performance, 44 GHz.

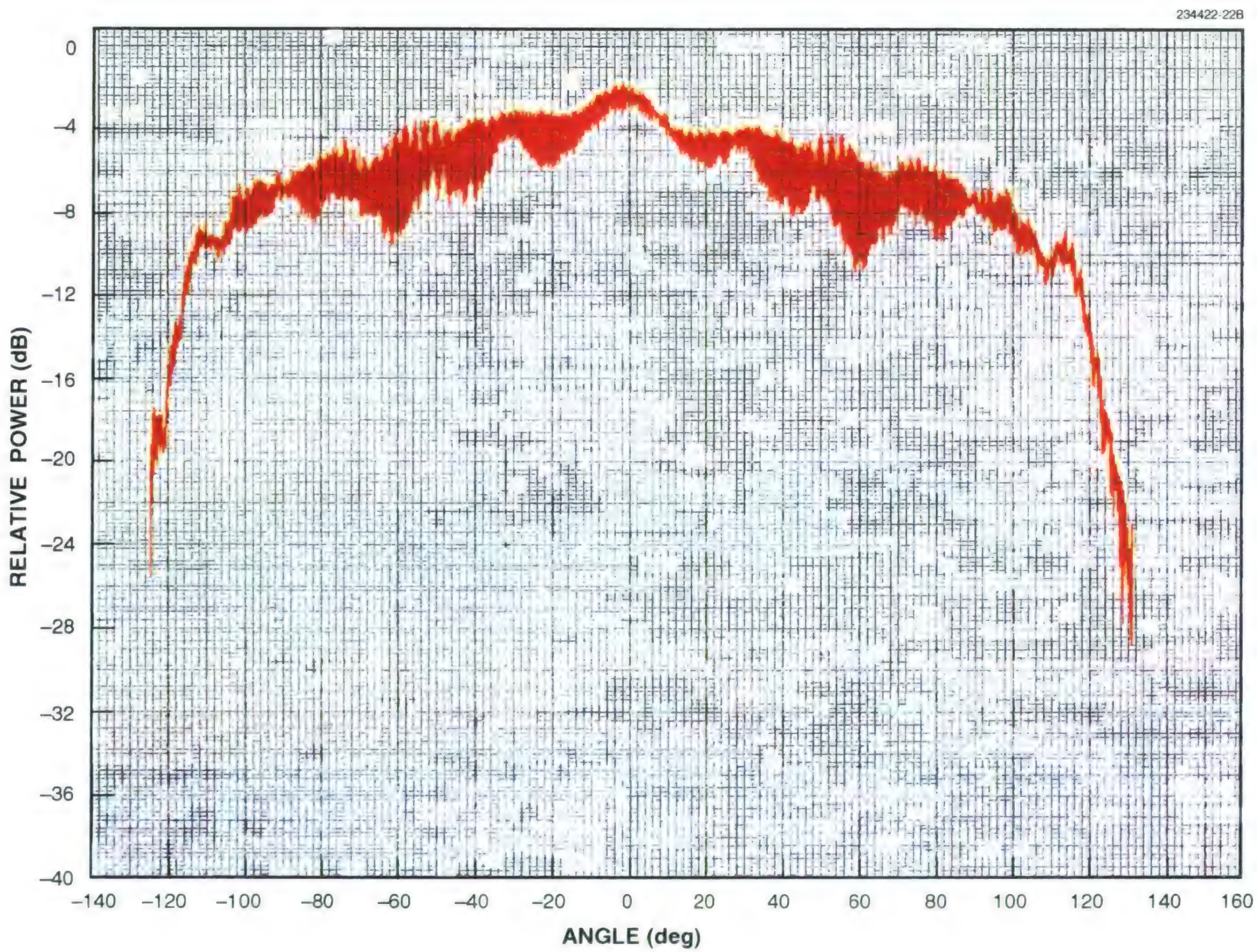

Figure 22. Q-band antenna performance, 45 GHz.

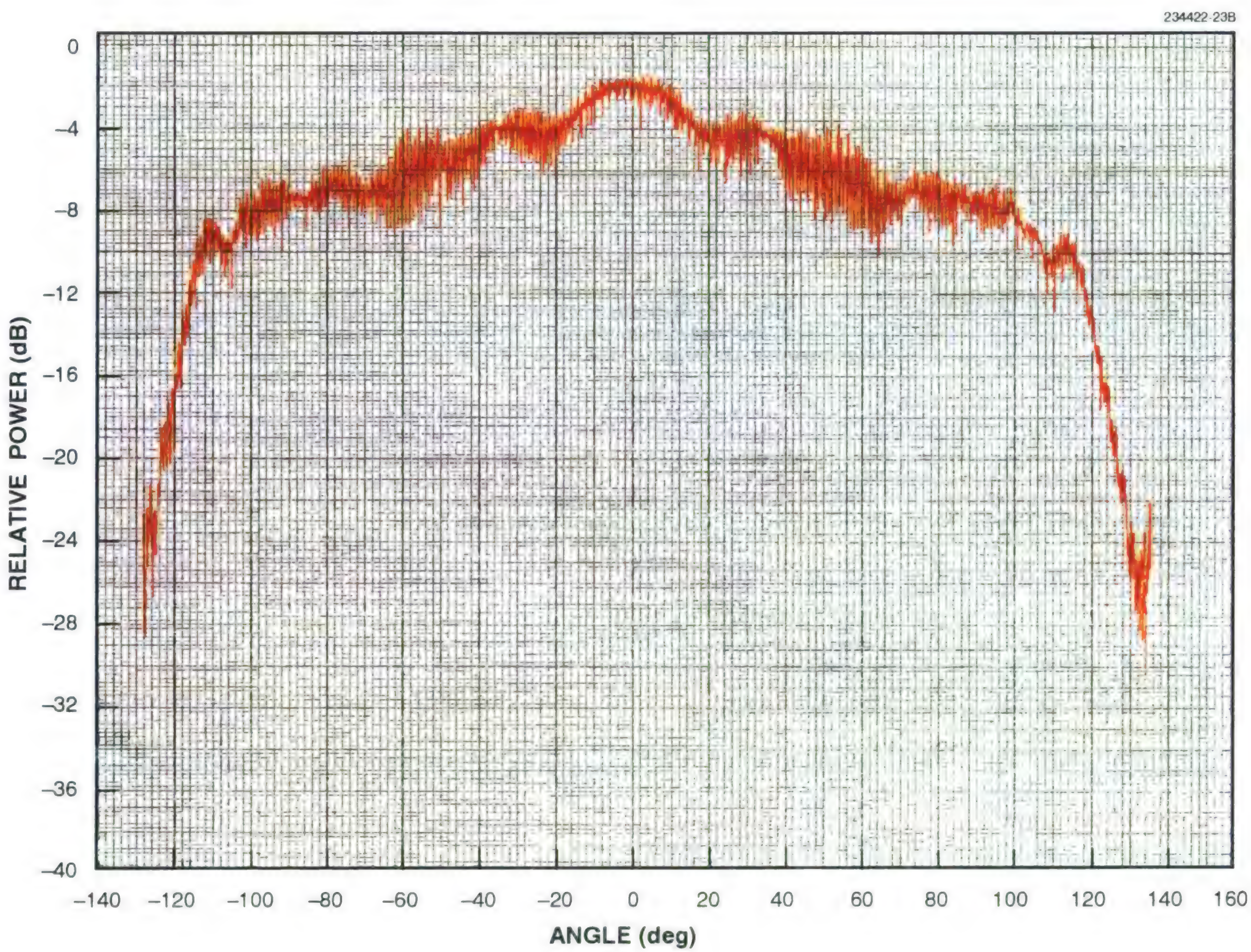

Figure 23. Q-band antenna performance, 46 GHz.

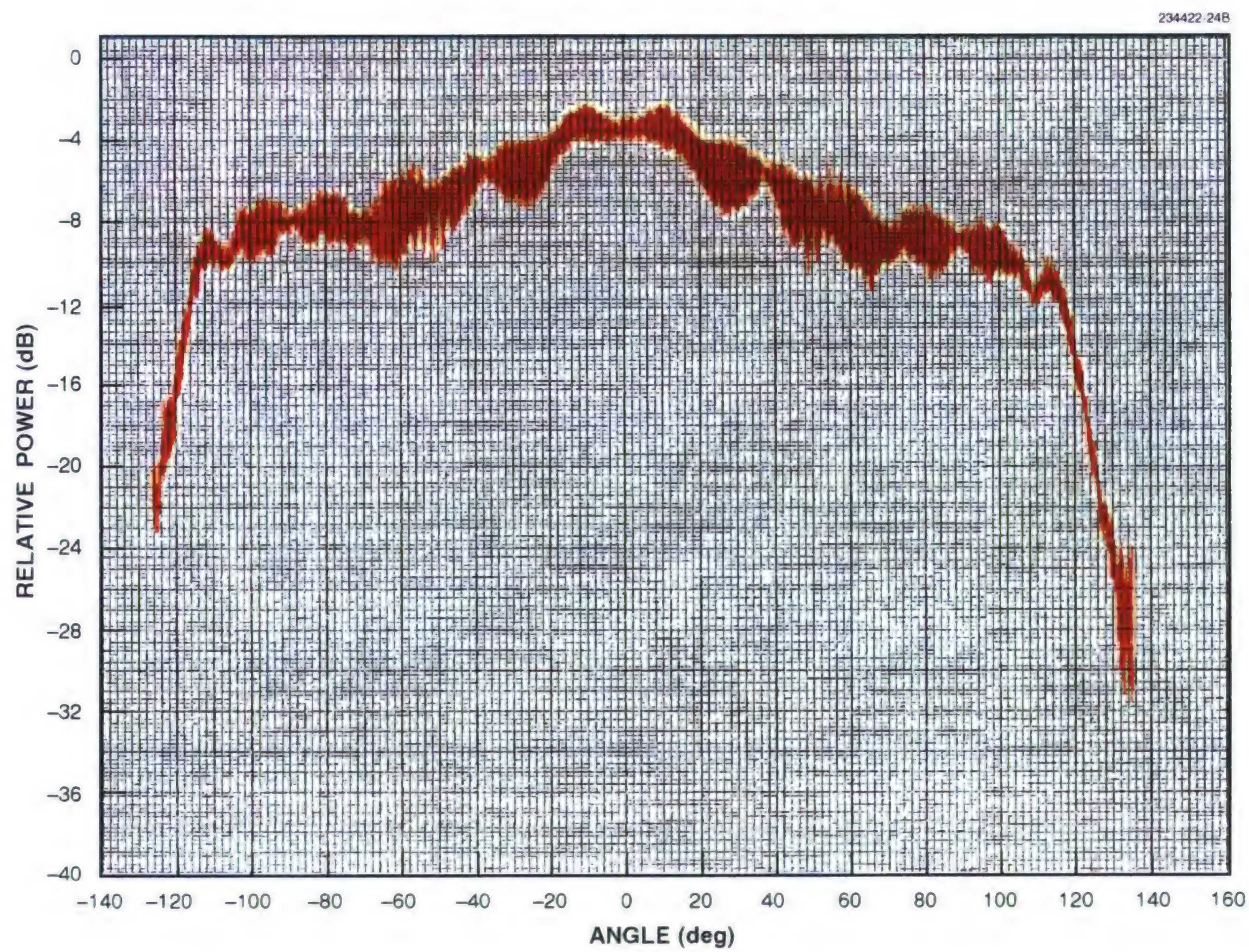

Figure 24. Q-band antenna performance, 47 GHz.

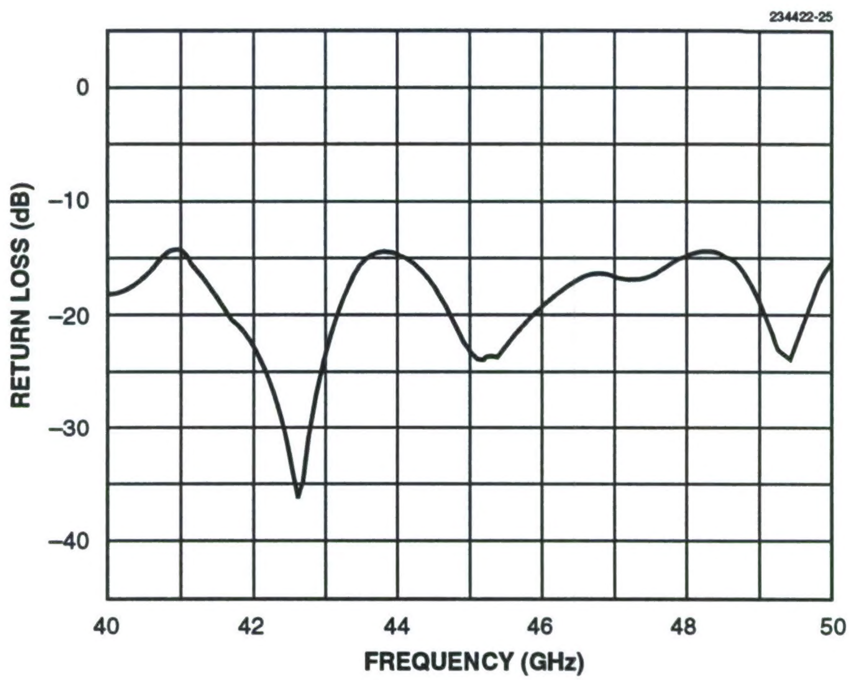

Figure 25. Q-band antenna match characteristics.

5. CONCLUSION

Work reported here demonstrates that a very wide and axially symmetric beam antenna with circular polarization, good axial ratio, and wide-band impedance match, can be achieved by using a simple dielectric ring in conjunction with a dielectric loaded circular waveguide opening. Mechanically, the antenna is small, lightweight, and low cost. The dielectric used is the common Rexolite. Since no foam and lossy materials or resonant scatterers are required, the antenna performance is inherently broadband and low loss.

For applications that require high power or high temperature operation, fused quartz and boron nitride could be used for the dielectric ring and rod. A sloping septum metallic polarizer could also be used in place of the simple dielectric quarter plate design.

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